Effect Assessment of Airflow Resistance by Local Airway Stenosis with 3D Printing Airway Model

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Abstract: Clinically noticing airway constriction can randomly cause small airway quickly closed and the surrouding airway occlusion happens subsequently. A phenomenon may happened called "avalanche phenomenon" inside airway [1]. But few study on how local airway stenosis affects the respiratory flow. Because the real local airway stenosis and its flow are still unable to be directly observed and measured. In this paper, narrow numerical model of the main and branched airway are established based on CT data of normal human airways. Then the trachea and bronchial branched airway constriction models are printed out on the 3D printer by PLA material. Finally, to measure airflow impedance of different airway models and analyze the impact of structural changes in the airway (shrink and narrow) airway impedance, we adopt independent research and development Forced Oscillation Technique(FOT). The test results preliminary show that the trachea stenosis has big effect on the airway viscous resistance (Rrs) and the elastic resistance (Xrs). The bronchial stenosis obviously increases the airway elastic resistance. This article provides a new method for the study on how local constriction affects the airflow inside airway in the future.

Keywords: Trachea, Bronchial, Local stenosis, Avalanche, Impedance.

INTRODUCTION

With Chinese economy rapid development, air pollution including fine particulate matter (PM2.5) pollution problems have become increasingly prominent. Harm of various respiratory diseases are boiling up. Currently, every year in China due to respiratory diseases, around 1million people die, 5 million people unable to work [2].

Airway stenosis becomes a main respiratory disease [3]. Asthma is most common respiratory disease clinically. One of its main pathologic feature is airway over constriction, but pathologic mechanism of airway over constriction has so far failed to explain well [4].

Observation found, airway over constriction can randomly occur on different bronchial local area, local airway constriction may lead to close of surrouding airway, which further lead to so-called "avalanche phenomenon" inside airway, threatening the lives of patients [5].

Forced Oscillation Technique, FOT is used by Dubois first time in 1956 for study of mechanics of respiration system. This technique is that a oscillation generator generates a pressure oscillation with specific frequency and amplitude, the oscillation wave applied to subject's oral and superimposed on the respiratory flow, into the airway and lung tissue with air, measure pressure and flow rate absorped and refracted by airway and lung tissue, calculate the quotient of oscillation pressure and flow rate based on Fourier transform, to obtain respiratory system impedance, Zrs; Zrs = Rrs + jXrs) [6]. The measured average value of respiratory system resistance, Rrs and respiratory system reactance can reflect airway structure (like airway stenosis) change [7], and distinguish airway impedance characteristics of normal and asthmatic [8].

As technically can not test out local airway constriction outside human body, and analyse its effect to whole airway flow. Current studies based on invisible spectro experiment. Current invisible spectro experiment is lack of real airway stenosis model, its result can not reflect real circumstance. But with development of 3D print technique, people can construct real human airway stenosis model outside human body [9].

Based on these technology, we made use of the medical imaging and 3D printing technique, to construct the human normal airway models and the stenosis airway models at different positions, and then took advantage of the Forced Oscillation Technique (FOT) to rapidly test the flow impedance of the normal

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and stenosis airway, and further analyzed the effect of the stenosis airway in different parts on the flow impedance value.

2. MATERIALS AND METHOD

2.1. 3D Print Real Airway Stenosis Model

Using computed Tomography (CT) to gain geometry data of human airway construction, import to mimics 17.0 for reconstruction of 3D models tomography [10], process models with 3d-matic to build following 3 kinds of airway models: 1) normal airway model as Figure **1**(**a**), **2**) trachea stenosis model, make stenosis in position 28.2 mm away of jugate in normal airway model, diameter change 16.1 mm to 9.8 mm as Figure **1**, **3**) bronchial stenosis model, make stenosis in position 4.5mm away of jugate in normal airway model, diameter change 13.7 mm to 8.3 mm as Figure **1**. Based on reconstructed three-dimensional airway model, print it out with makerbot replicator 2 and materials PIA, built physical map as Figure **2**.

2.2. The in-House Built Instrument for Measuring Airway Impedance Based on Forced Oscillation

Self-developed forced oscillation examiner (FOT) consists following parts:oscilation source, pressure sensor, flow sensor, data acquisition card and computer.

The main principle is piston as oscillation generator (Figure **3**) driven by voice coil motor, output oscillation wave with 5Hz, 2.5 cm H2O Amplitude sinusoidal pressure [11], and plug it into printed airway through pipe (internal diameter 25 mm, length 50 cm) of low resistance and high inertia. Design of intubation ensure the air flow inside pipe. We use NI USB-6211 data acquisition card to collect data from pressure and flow sensors, collected signals firstly hadrware filtered

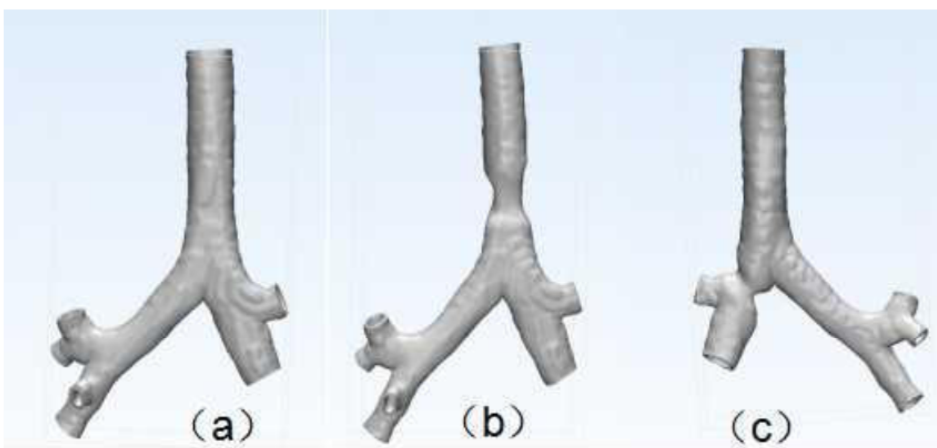

Figure 1: Images of the reconstructed 3D models of the three types of airway stenosis. (**a**) 3D model of normal airways（**b**）3D model of trachea stenosis (**c**) 3D model of bronchial stenosis.

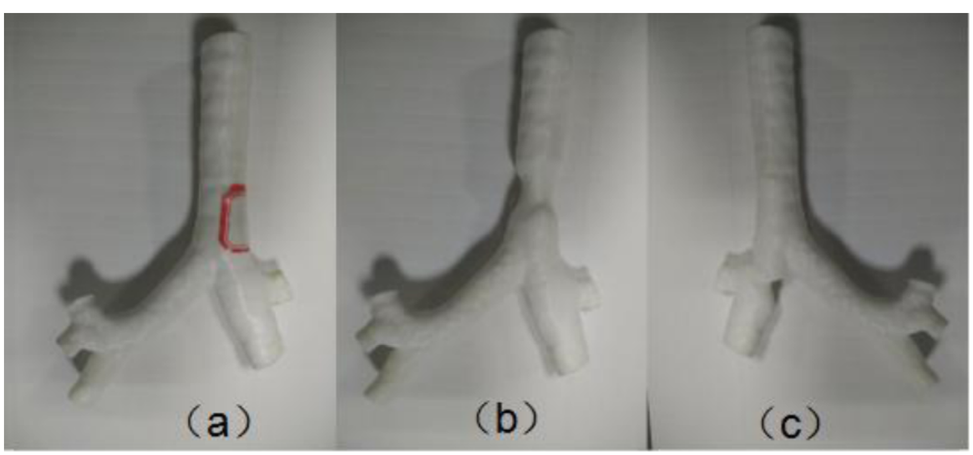

Figure 2: Images of 3D printed mocks of the three types of airway stenosis. (**a**) the normal airway（**b**）the trachea stenosis (**c**) the bronchial stenosis.

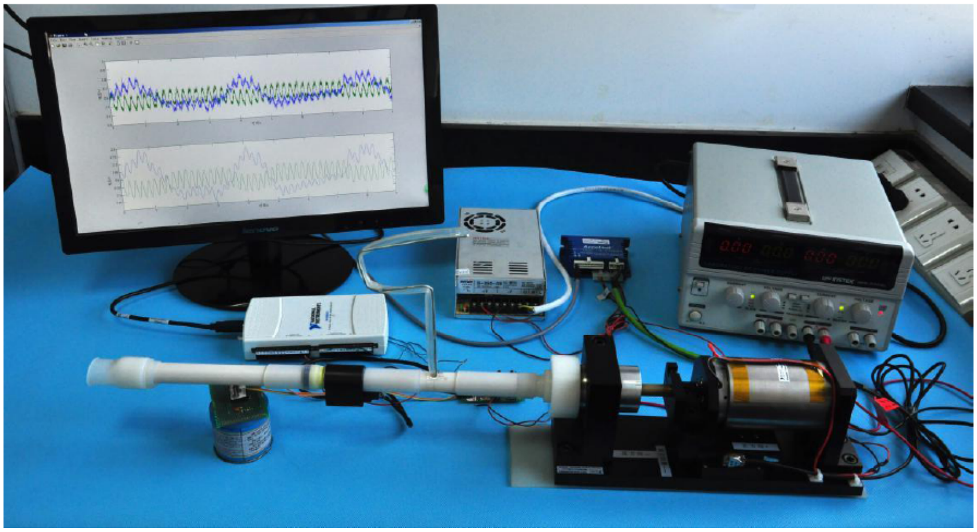

Figure 3: The in-house built instrument for measuring airway impedance based on forced oscillation technique.

through low pass filter, acquisition card collect signals of pressure and flow simultaneously, and the signal is transmitted in real-time to computer for processing calculations.

2.3. Calculation of Respiratory System Resistance

For calculation of respiratory system resistance, we used a frequency domain analysis method adopted from that as reported by Horowitz *et al.* [9]. For a given oscillating pressure P(t) and corresponding flow V(t) measured from the respiratory system, the total respiratory system impedance (Zrs) was

$$Zrs = P(t)/V(t) \tag{1}$$

Zrs was a complex quantity that contained a real, and an imaginary part, which could be expressed as:

$$Zrs = Rrs + jXrs \tag{2}$$

Rrs was the component in the same phase of the pressure and flow signals that reflected the viscous resistance of the airways and the lung tissues. Rrs was mainly due to the large to small airways, therefore is termed respiratory system resistance or airway resistance. Xrs was the component out of the phase of the pressure and flow signals that reflected the elastic and inertial resistance of the airways and the lung tissues. Xrs was mainly due to the small bronchi and the lung tissues (elastic resistance) and the airways and the chest (inertial resistance).

P(t) and V(t) are both time varying functions. By using triangular form of Fourier series, they could be transformed as the following:

$$P(t) = a_0/2 + \sum_{k=1}^{\infty}(a_k \cos 2\prod fkt + b_k \sin 2\prod fkt) \tag{3}$$

In the equation, $t_1 - T/2 \le t \le t_1 + T/2$, t_1 was any point in time and $a_0/2$ was the DC component of the cycle function. a_k and b_k were real number that related to system response to external signals , k=1,2,3...... ∞ ,

$$a_k = \frac{2}{T}\int_{t_1-T/2}^{t_1+T/2} P(t)\cos 2\prod ftdt \tag{4}$$

$$b_k = \frac{2}{T}\int_{t_1-T/2}^{t_1+T/2} P(t)\sin 2\prod ftdt \tag{5}$$

Thus, the amplitude of the oscillating pressure at t_1 was:

$$|P|_{t_1} = \sqrt{a_k^{\ 2} + b_k^{\ 2}} \tag{6}$$

and the corresponding phase was:

$$\theta(P_{t_1}) = \arctan(-b_k/a_k) \tag{7}$$

Similarly, the amplitude of the oscillating flow was $|V|_{t_1}$, and the phase was $\theta(V_{t_1})$.

Accordingly, the amplitude and the phase of the impedance were:

$$|Z|_{t_1} = |P|_{t_1}/|V|_{t_1} \tag{8}$$

$$\varphi(t_1) = \theta(P_{t_1}) - \theta(V_{t_1}) \tag{9}$$

The amplitude and phase of the respiratory impedance at t_1 were $|Z|_{t_1}$ and $\varphi(t_1)$, respictively.

The respiratory system impedance was then expressed in the form of respiratory system resistance (Rrs) and reactance (Xrs) as:

$$|Z_{rs}| = \sqrt{R_{rs}^{\ 2} + X_{rs}^{\ 2}} \tag{10}$$

$$\varphi_{rs} = \tan^{-1}\frac{X_{rs}}{R_{rs}} \tag{11}$$

Therefore,

$$\begin{aligned} Rrs &= Z\cos\varphi \\ Xrs &= Z\sin\varphi \end{aligned} \tag{12}$$

Thus, the respiratory system resistance at each time point was calculated.

2.4. Experimental Procedure of Actual Measurement

Measured airway model are connected to FOT airway impedance examiner via interface pipe, and seal the connection point of airway model and interface pipe with rubber tube, as leakage can cause inaccurate results during measurement. Each measurement last 3 min, each model to be measured five times repeatedly. Input pressure signal of sine wave 5 Hz. Use Lab View with the NI USB-6211 data acquisition card to collect signal, the signal are sampled with rate 250 kS / s. The whole single precessing is carried out in the MATLAB platform. Late statistically analyze and compare results from normal airway model, trachea stenosis model and bronchial stenosis model.

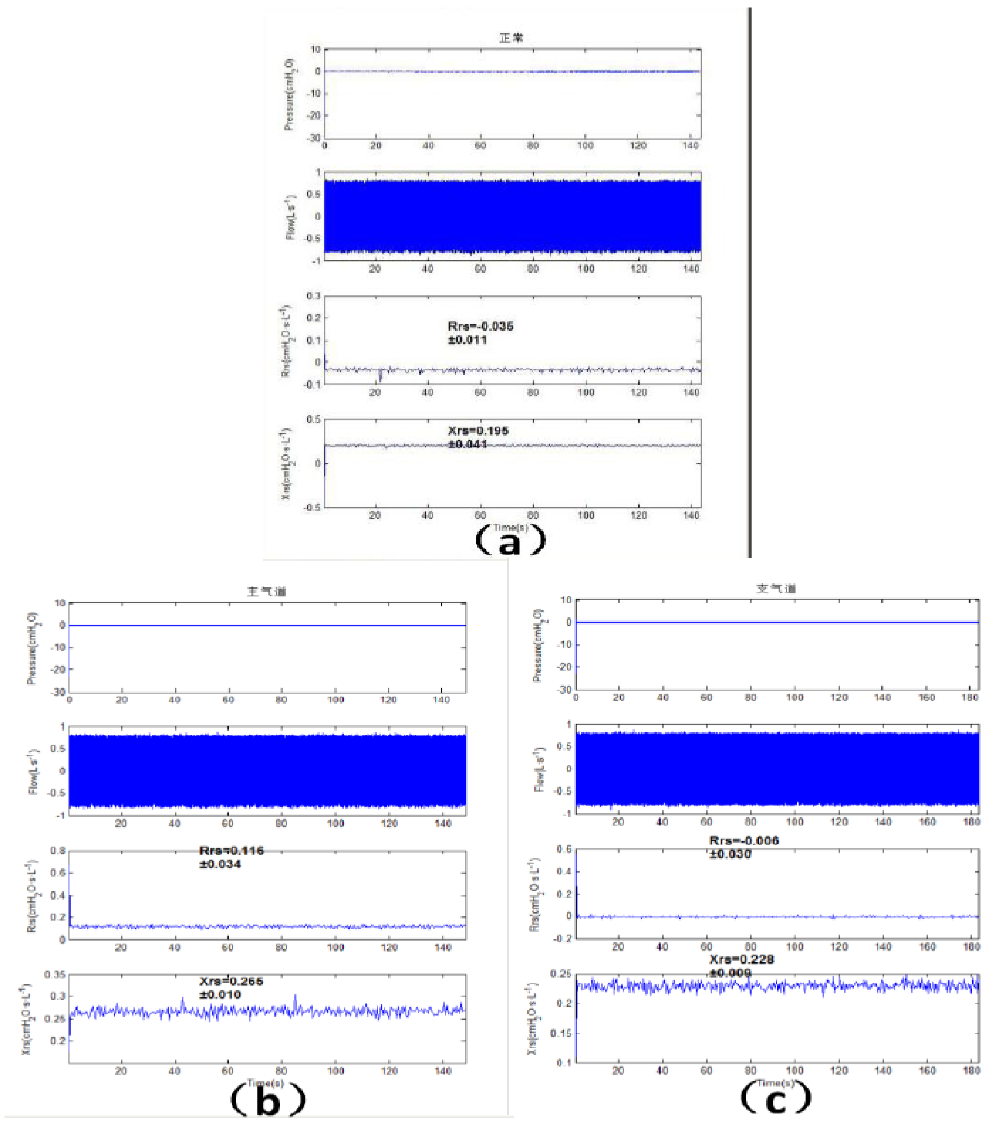

Figure 4: MATLAB Calculation model of the airway results values Rrs and Xrs. (**a**) is calculation result figure of normal airway model, (**b**) is calculation result figure of trachea stenosis model (**c**) is calculation result figure of bronchial stenosis model.

Table 1: Airway Resistance (Rrs) and Reactance (Xrs) of the Three Types of Airway Stenosis

Airway Model / Impedance Value	Normal Airway Model	Trachea Stenosis Model	Bronchial Stenosis Model
Rrs	-0.035±0.011	0.116±0.034	-0.006±0.030
Xrs	0.195±0.041	0.265±0.010	0.228±0.009

3. RESULTS AND DISCUSSION

Experimental data collected by NI USB-6211 data acquisition card about flow and pressure, processed with MATLAB platform, output three group of experimental results as Figure **4**. (**a**) is calculation result figure of normal airway model; (**b**) is calculation result figure of trachea stenosis model ;(**c**) is calculation result figure of bronchial stenosis model. In the result figure, the first low is pressure waveform, second low is flow waveform, three low is Rrs value, fourth low is Xrs value.

Table **1** is test result of normal airway model, trachea stenosis model and bronchial stenosis model. From this table, Rrs value of trachea stenosis model significantly higher than value of normal airway model, amplitude approximately 430%, Xrs value of bronchial stenosis model slightly higher than value of normal airway model, amplitude approximately 17%.

4. CONCLUSION

The experiment result shows position of airway stenosis reflect to airway resistance differently. The trachea stenosis has big effect on airway viscous resistance (Rrs) and elastic resistance (Xrs), the bronchial stenosis mainly effect airway elastic resistance (Xrs).

It follows that, actual model of real human airway and its stenosis based on 3D print technique, combined with airway resistance measurement technique (like FOT), can provide possibility for study the effect of real human airway stenosis to airy flow function, even can judge if the airway constriction occur, and possibility to find place of constriction, then can provide new ideas and new methods to achieve early detection and early diagnosis of airway stenosis.

In the future, we will perform the following tasks: selecting patients with a number of airway stenosis and measure the mean of respiratory resistance and respiratory system reactance using FOT technology. Then CT scans are performed on these patients to obtain the data of the airway structure, and generate a 3D model. The model will be printed out by PLA material with a 3D printer, and the numerical value of the resistance of the respiratory system and the reactance of the respiratory system can be measured. Finally, we will compare the two sets of data to verify whether airway resistance can reflect the position of airway stenosis.

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